Finite CA, Total Pc, and a Substantially-Larger Catalog

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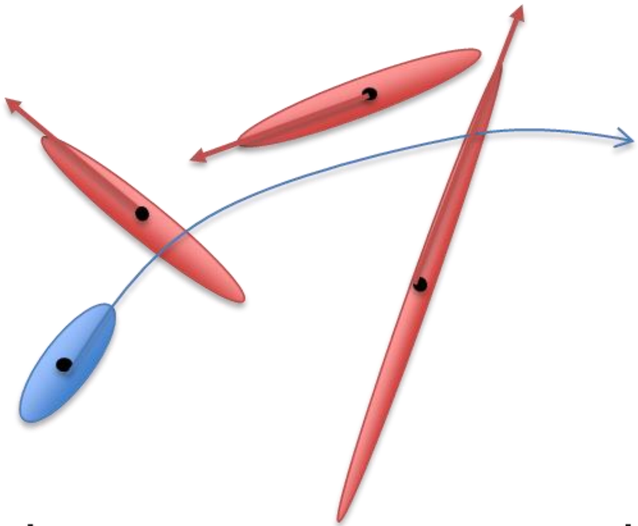
Overview

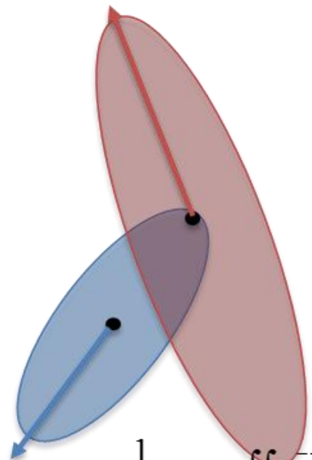
- The “CA Problem”
- CA with a Substantially-Larger Catalog
- The Total Collision Probability Metric (TPc)
- TPc in Collision Risk Mitigation Operations
- TPc in Collision Risk Assessment Operations
- Operational Considerations
- Finite CA Advanced Concepts
- Conclusions & Future Work

On-Orbit Collision: A Real Mission Risk

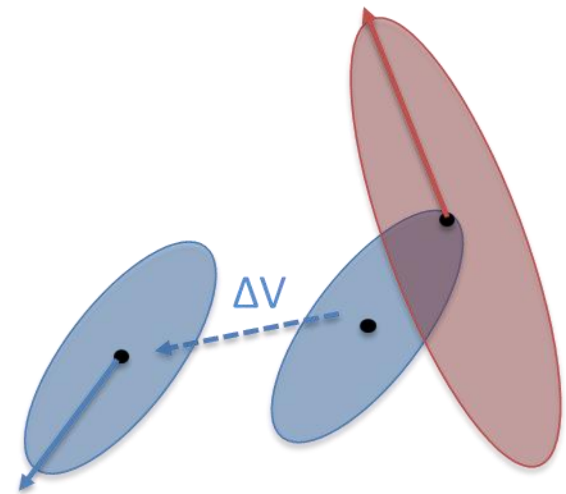
- **Most mission stakeholders believe on-orbit collisions are real threat**
  - JSpOC detecting, tracking, and maintaining high accuracy space object catalog using the Space Surveillance Network
  - JSpOC notifying owner/operators of close approaches
  - Several documented cases of collisions in space
- **Space object environment continues to "grow'**
  - More objects launched into space: increasing reliance on space domain for military, civil, commercial, and humanitarian efforts
  - More objects generated in space: on-orbit break-ups from explosions or collisions continue to generate small-to-large debris clouds
  - More objects observed in space: Improved technologies and systems planned to track smaller debris (Space Fence) and manage that data (JSpOC Mission System, JMS)
- **Awareness of mission risk + awareness of increasing mission risk**
  - Most owner/operators have some process or system in place to help manage collision risk
  - "Big Sky" no longer a legitimate CONOPS

Typical On-orbit Collision Risk Management





$$P_c = \frac{1}{2\pi\left[\det(\mathbf{C})\right]^{1/2}} \iint_A e^{-\frac{1}{2}x^{\mathrm{T}}\mathbf{C}^{-1}x}\, dA$$



Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction "screening"

The **CARA detachment** at the **Joint Space Operations Center (JSpOC)** screens CARA-supported assets against the catalog, assists with OD and tasking for identified conjunctions, and generates close approach data

CA Risk Analysis (CARA) is the process of assessing collision risk and assisting with maneuver planning to mitigate that risk, if warranted

The **CARA** Team at NASA-GSFC provides CARA for all NASA operational robotic satellites, as well as a service provider for some other external agency/organizations

Collision Avoidance (COLA) is the process of executing mitigation actions, typically in the form of an orbital maneuver, to reduce collision risk due to a conjunction

Each satellite **Owner/Operator (O/O)** – mission management, flight dynamics, and flight operations – are responsible for making maneuver decisions and executing the maneuvers

Managing On-Orbit Collision Risk Is Not Easy

- **Even with a robust CONOPS in place, reacting to on-orbit collisions is not easy**
  - Disruptive to mission and operations
  - Presents challenges for decision-makers
  - Resource-intensive
- **For reference, a satellite in a 700-km sun-synchronous orbit today manages on average**
  - 25-40 close approach notifications per month
  - 1-4 high-interest events per month
  - 1-2 collision avoidance maneuvers per year
- **Space Fence to create substantially-larger catalog**
  - Current estimates anywhere from 60,000 – 100,000 object catalog size
- **This expected increase will challenge the way we conduct collision risk management and operations**

Finite CA

- **Increasing risk/workload is not a new problem**
  - JSpOC already making architectural investments and modifications
  - Many groups already looking at processing problem—GPUs, Clouds, and other technologies may have great applicability in this mission
  - Active Debris Removal appears to be moving from science fiction to mainstage
  - CARA already developed and implemented some systematic and procedure modifications to help triage events
- **Solutions to all of the above does imply that we are poised to handle a substantially-larger catalog**
- **Propose here a paradigm shift in the treatment of individual conjunctions**
  - Today we assess each conjunction individually, as a discrete event
  - It is possible to convolve collision probabilities from discrete conjunctions into a single, total probability of collision—a total Probability of Collision (TPc)
  - ***Finite CA*** is the treatment of all predicted conjunction over a finite period of time as a single mission risk
- **In doing so, some parts of present CONOPS can be preserved, others adapted**

Total Collision Probability (1 of 2)

- **For simplicity, consider 3 <u>independent</u> events (A, B, and C, each with probabilities P_A, P_B, and P_C)**
  - No correlation or conditional probability between them
  - Can easily be generalized to *n* events
- **The probability of at least one of them occurring can be calculated by a simple formula produced by de Morgan's Law of Complements:**

$$P(A \cup B \cup C)$$

$$= 1 - \overline{P(A \cup B \cup C)} \quad (1)$$

$$= 1 - (\overline{P_A} \cap \overline{P_B} \cap \overline{P_C}) \quad (2)$$

$$= 1 - (\overline{P_A})(\overline{P_B})(\overline{P_C}) \quad (3)$$

$$= 1 - (1 - P_A)(1 - P_B)(1 - P_C) \quad (4)$$

$$= P_A + P_B + P_C - P_A P_B - P_B P_C - P_A P_C + P_A P_B P_C \quad (5)$$

Total Collision Probability (2 of 2)

$$= 1 - \overline{P(A \cup B \cup C)} \qquad (1)$$

$$= 1 - (\overline{P_A} \cap \overline{P_B} \cap \overline{P_C}) \qquad (2)$$

$$= 1 - (\overline{P_A})(\overline{P_B})(\overline{P_C}) \qquad (3)$$

$$= 1 - (1 - P_A)(1 - P_B)(1 - P_C) \qquad (4)$$

$$= P_A + P_B + P_C - P_A P_B - P_B P_C - P_A P_C + P_A P_B P_C \qquad (5)$$

- **Independence assumption used in moving from (2) to (3)**
  - Conjunctive probabilities (*e.g.*, "P_A and P_B") calculated by direct multiplication, rather than consideration of conditional probability
- **Product terms in (5) adjust for the "double counting" of situation in which intersection of sets A, B, and C counted multiple times in simple summation of probabilities**

Independence of Conjunction Events (1 of 2)

- **Groups of conjunctions with same primary and different secondaries would appear so**
  - No reason to believe that proximity to one secondary would affect potential proximity to a second, unrelated secondary
- **Repeating conjunctions a different case**
  - Some amount of correlation/dependence may inhere
- **Monte Carlo investigation of repeating conjunction event**
  - Three repeating conjunctions, all high Pc (>1e-04)
  - One million trials run
  - Primary and secondary position perturbed at epoch (according to covariance); propagated forward; new TCAs found; violations of HBR tabulated
    - For each conjunction independently
    - Violation of any of the three events
  - Results summarized in table

Independence of Conjunction Events (2 of 2)

Attribute		Equinoctial	Cartesian
From Monte Carlo	P_A	1.38E-03	1.36E-03
	P_B	8.20E-04	8.31E-04
	P_C	6.31E-04	7.16E-04
	Any compound terms ($P_A P_B$ &c.)	0	0
	P_A or P_B or P_C	2.84E-03	2.91E-03
Formula calculation from P_A, P_B, and P_C above		2.84E-03	2.91E-03
Formula calculation from 2-D Pc values for each event		2.29E-03	
Difference between MC and 2-D Pc (in orders of magnitude)		0.094	0.105

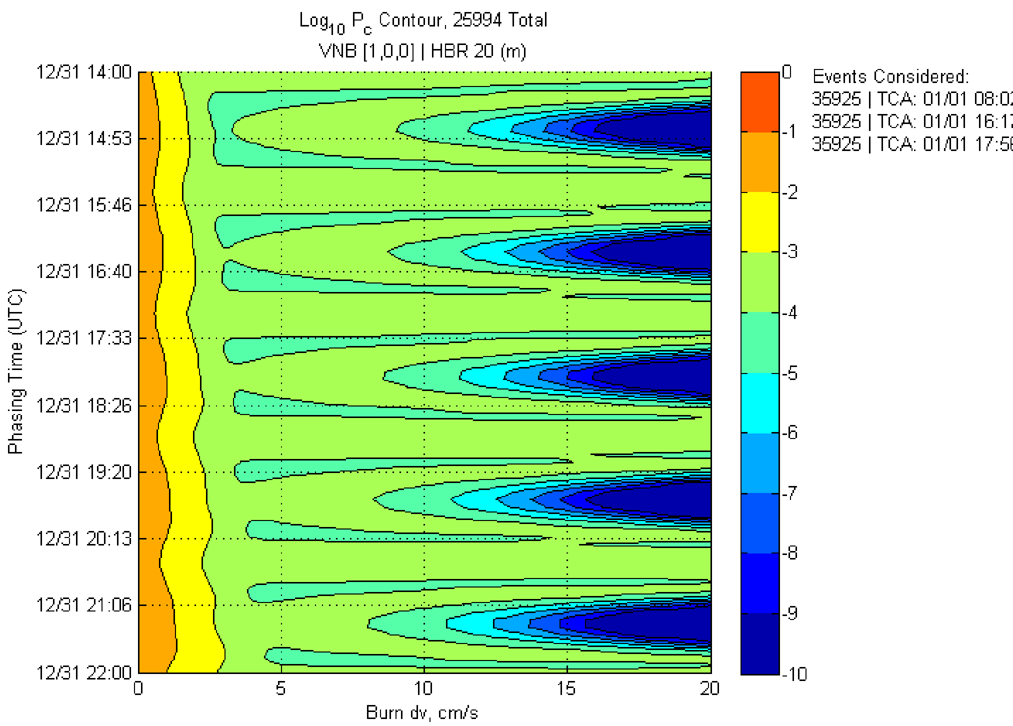
- **No compound situations observed**
  - Odd result, as at least a few such situations should arise with 1,000,000 trials
- **However, actual tabulation matches formula to three significant figures**
- **Match to formula calculation from 2-D Pc values better than one tenth an order of magnitude**
- **More exploration needed, but results encouraging**
  - Formula works well even in circumstance where correlation/dependence suspected

TPc in Finite CA Risk Management

- **For now, let's assume the independence assumption is valid in all cases**
- **How can we use the TPc for collision risk management?**
  - For Finite CA risk assessment: is the total risk of collision to my satellite significant enough to warrant evasive action
  - For Finite CA risk mitigation: how can I reduce the total risk by executing an orbital maneuver?
- **Analogous to Pc for discrete CA**
- **We will discuss risk mitigation operations first**

Finite CA Collision Risk Mitigation

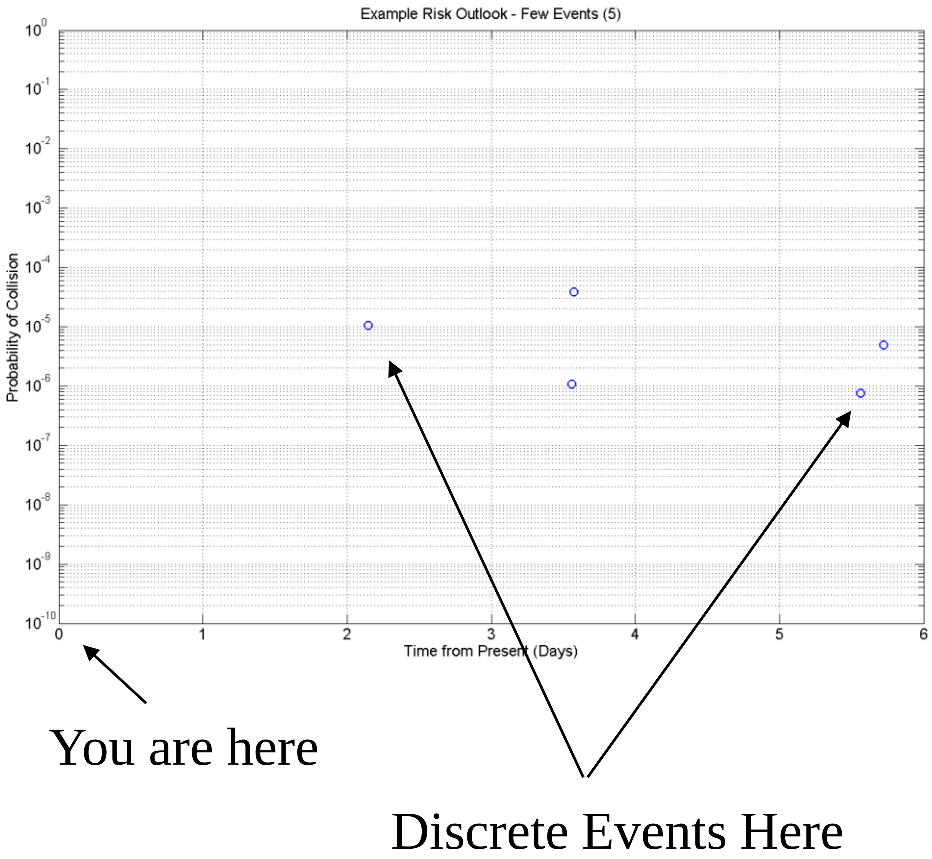
- **When a decision has been made to plan an avoidance maneuver, consideration of the maneuver's effect on other conjunction is straightforward**
  - In fact, simplest form of this consideration is by screening the candidate maneuver(s)
- **Maneuver Trade Space (MTS) now a common tool for assisting with avoidance maneuver**
  - Provides insight into post-maneuver Pc with timing and ΔV sizes



- **Use of TPc in MTS a more direct consideration of other post-maneuver conjunctions**
  - TPc property: post-maneuver Pc for any considered event ≤ post-maneuver TPc

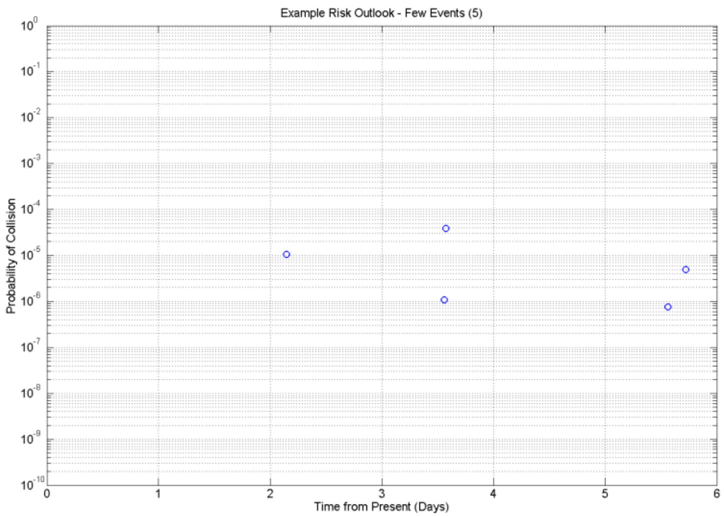
Finite CA Collision Risk Assessment

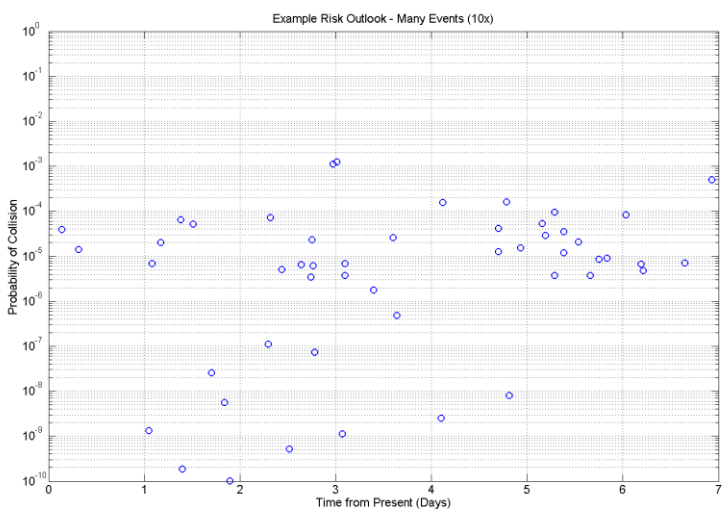
- **At any given point in time, there is a finite number of discrete conjunction events through end of the prediction period**
  - Events range in severity and time to TCA
  - Graph on right shows a sample risk outlook
- **As time progresses, new predictions are received that change risk (Pc) and reaction time**
- **At some point in time when these criteria breach threshold, avoidance maneuver planning is triggered**
  - Typically, there is a single trigger event

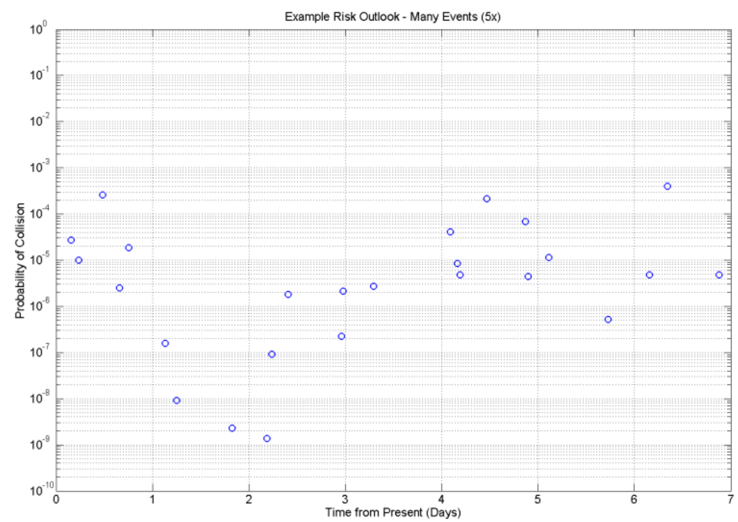


Finite CA Collision Risk Assessment

- **What happens when there are multiple high-risk conjunctions predicted?**
  - When is the first risk?
  - When is the first risk over my threshold?
  - When is the most significant risk?
  - When is the last risk?
- **Clockwise; a representative risk outlook with 1x, 5x, and 10x present-day sized object catalog**

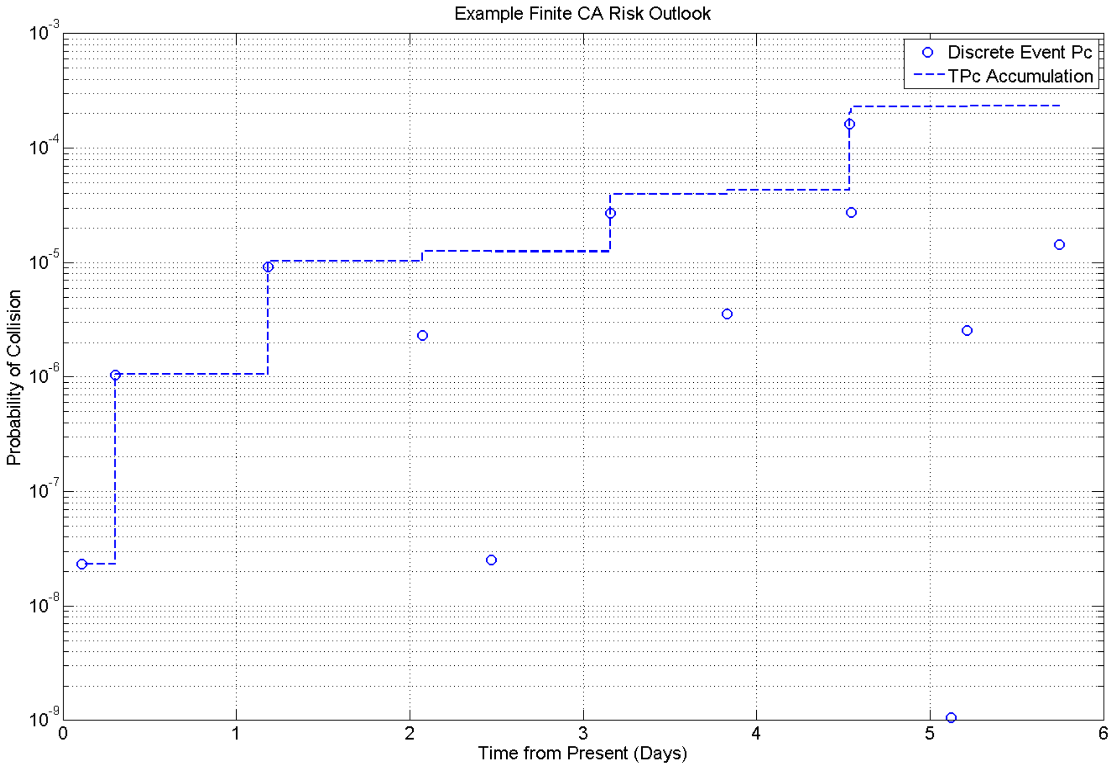






Finite CA Risk Assessment

- **TPc convolves Pc for each discrete event**
- **Can be expressed as single metric**
  - That value is the probability that any one of the conjunctions Results in a collision
- **Can also consider how TPc accumulates over the prediction period**
  - Example shown on right
- **In this paradigm, no single event triggers action but the total risk situation does**

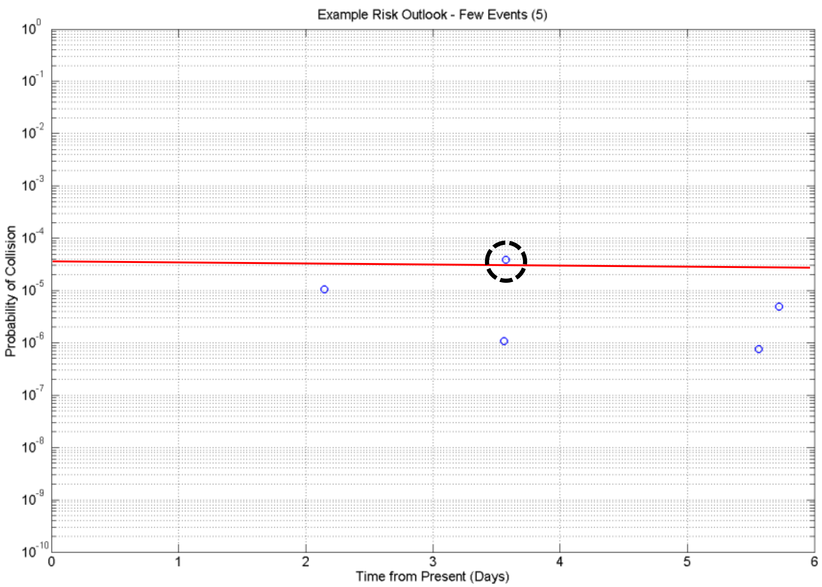


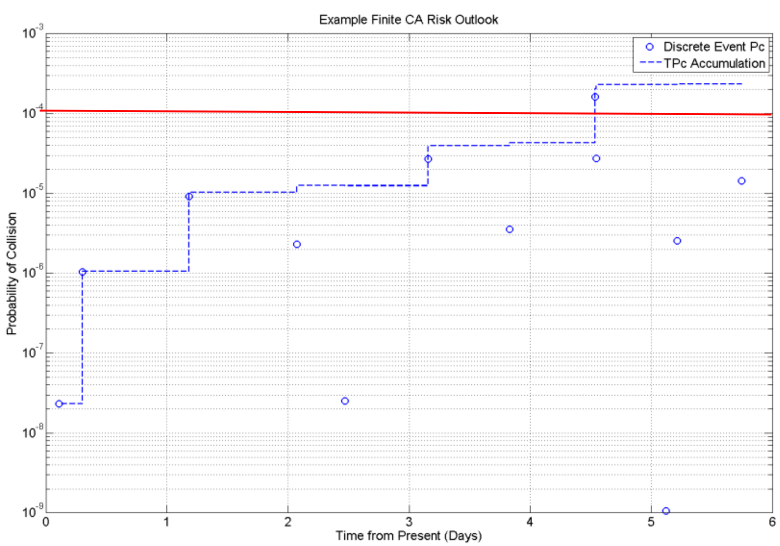
Advantages of Total Pc for Finite CA

- **Easier to manage**
  - For any given period of time, there is a single on-orbit collision risk
  - No inherent limitation
- **Does so while retaining physical significance**
  - Provides probability that any one of the conjunctions results in a collision
- **Prevents “false sense of security” when many low risk conjunctions are present**
  - Death by a thousand cuts scenario
- **TPc accumulates provides insight into overall risk metric**
  - Identifies “gaps” for potential remediation windows

Operational Considerations

- **In theory,**
  - Discrete CA (top): if Pc ≥ threshold, plan (and execute) maneuver
  - Finite CA: if TPc ≥ threshold, plan maneuver
- **In practice, however, some other aspects that enter the decision calculus; such as:**
  - Timing of conjunction event(s)
  - Quality of input data
  - Maneuver sizes required to mitigate risk sufficiently w.r.t mission constraints
  - Mission operations
  - Other mission risks
- **These considerations still exist if not exacerbated in the Finite CA**
  - There will always be challenging conjunctions



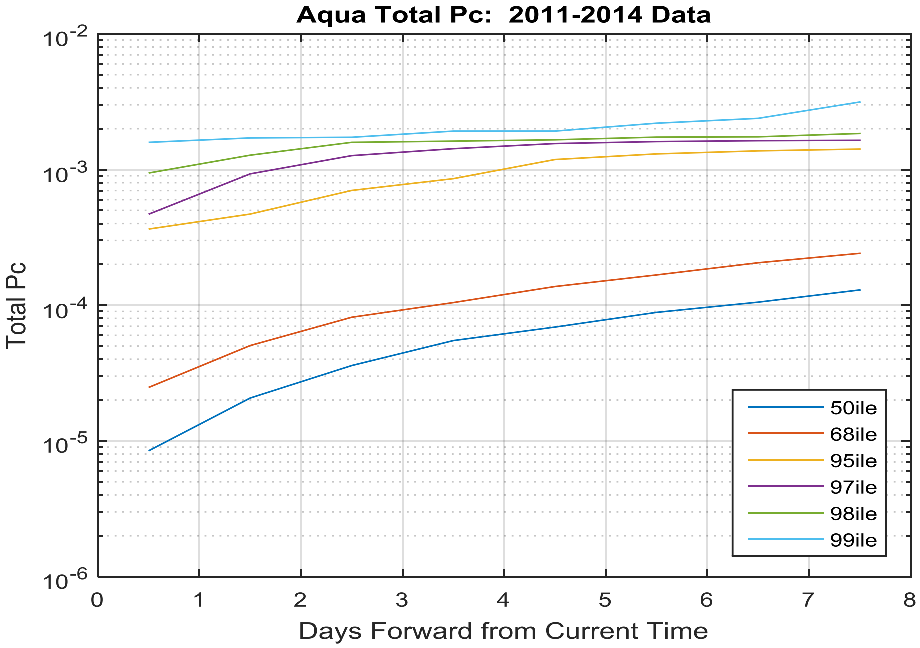


Operational Considerations: Quality & Timing

- **The Pc (and TPc) should reflect data quality and timing of events**
  - Both calculations include state uncertainty information by way of the objects' covariance
  - Covariance should represent effects of sparse-tracking or long propagation times
- **Covariance scaling not a unidirectional effect on Pc (let alone TPc)**
  - Over/under-estimation of covariance can increase or decrease Pc
- **Some CONOPS work around covariance realism assumption**
  - *i.e.,* Max Pc
  - May work fine for risk assessment, but attention must be paid for risk remediation and also imputed workloads in Finite CA
- **CARA currently uses quality information to direct OD remediation activities**
- **Could enfold quality into computation by "weighting" discrete Pc**
- **F-value was attempt to evaluate discrete conjunctions event by risk and quality (and event timing information)**
  - Loss of physical meaning—metric was more of a risk score than event likelihood

Operational Considerations: Quality & Timing

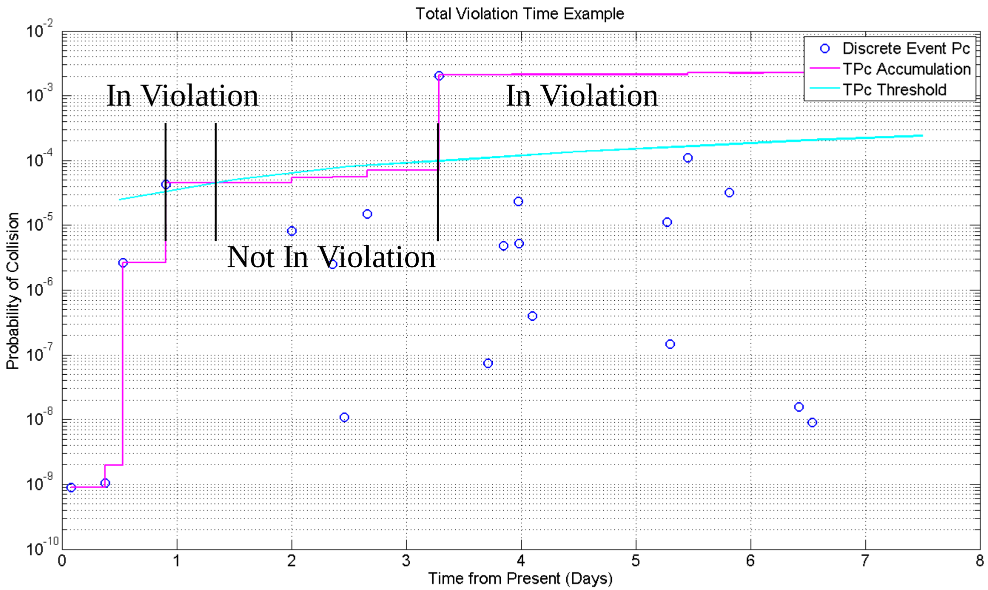
- **Another option is a time-varying TPc threshold**
  - TPc computation remains unchanged
  - Enables a more risk conservative posture overall
  - Could define time-varying threshold using empirical data (graph on right for Aqua data)



Finite CA Advanced Concepts

- **Total Pc Saturation**
  - As more and more discrete events are convolved, the quicker the TPc approaches unity
  - Though mathematically true, phenomenology not lose physical meaning
  - Could continue to increase risk threshold in kind but is there a operational limitation?
- **Total Violation Time**
  - Another, more complicated way to assess TPc against a TPc threshold is total amount of time (or percentage of time) that threshold is violated
- **Collision Avoidance as an Orbit Maintenance Strategy**
  - Use avoidance maneuvers to maintain orbital requirements
  - Avoidance maneuvers become the operational norm and a canned station-keeping maneuver is the "out-of-cycle"
  - Does provide advantage of allowing risk conservative posture *without* disrupting mission operations—an avoidance maneuver plays into orbital maintenance strategy rather than against it

Total Violation Time = ~ 4 days (57%)



Conclusions

- On-orbit collisions are a risk today
- That risk will continue to grow
- Managing that risk will challenge how we do business
- Treating all predicted conjunctions during a given prediction period as a single risk (Finite CA) may not be desirable but may be an unavoidable evolution
- The Total Collision Probability (TPc) offers some advantages as a risk metric
- Such a CONOPS once fully-fleshed out is likely one-step towards preparing for space operations in the future space environment